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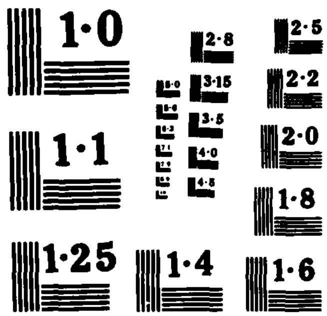
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MELBOURNE, VICTORIA

Systems Technical Memorandum 70

OBSERVATIONS OF LIGHTWEIGHT DOPPLER SYSTEM ACCURACY

I.V. LLOYD

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OBSERVATIONS OF LIGHTWEIGHT DOPPLER SYSTEM ACCURACY

by

I.V. LLOYD

SUMMARY

Data on the accuracy of the Lightweight Doppler Navigation System (LDNS) fitted to a Royal Australian Air Force UH-1H helicopter were gathered as a by-product of an experiment on the TACTERM navigation system. The observed accuracy was found to be close to 1% of distance travelled, a figure generally considered to be representative of modern doppler navigation systems.

The dominant source of LDNS position error was magnetic compass error which in turn appeared to be dominated by spatial and temporal variations in the local magnetic field.

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CONTENTS

1. INTRODUCTION

The Lightweight Doppler Navigation System (LDNS) is to be fitted to all R.A.A.F. UH-1H Iroquois helicopters. The first such installation in aircraft number A2-455 was used in experiments with the TACTERM navigation system in April/May 1983. Some data on the accuracy of the LDNS were produced as a by-product of these experiments.

These experiments were designed to assess TACTERM performance and were carried out to a very tight schedule which allowed little time for investigation of doppler errors. The experimental design was not as good as it might have been if more time were available.

2. PROCEDURES and RESULTS

The LDNS was required to be performing satisfactorily for the TACTERM experiments so a compass swing (calibration) was undertaken as the first action. The aircraft magnetic heading was observed by sighting a "Wild Datum" (two vertical bars fixed either side of the cargo compartment) wih a compass fitted with a telescope. The measured magnetic heading was compared with the aircraft AN/ASN-43 compass reading (as indicated by the LDNS) the difference being the compass 'deviation' (see Appendix 1). This was repeated for twelve headings at 30 degree nominal intervals. The engine was running and the aircraft systems were as close to normal in-flight conditions as possible.

The results of this swing did not conform to a reasonable pattern (see Appendix 1) and were not repeatable to within half a degree. The results are not recorded here. Since compass error is the primary source of the cross-track component of doppler error (see Secton 3) it was decided that compass errors could be assessed more accurately by flying along tracks between known points, recording the position error accumulated and resolving this error into cross-track and along-track components. The angle subtended by the cross-track component over the distance flown on the leg is the compass 'deviation'. The along-track error can be expressed as a percentage of distance flown. This procedure will henceforth be referred to as an "Air Calibration".

The pattern of tracks flown is shown in Figure 1. At the start of each leg the LDNS was initialised to agree with the true position. At each end point the LDNS display was 'frozen' while the indicated position was recorded prior to re-initialization for the new leg. One L-shaped pattern was flown at a time; out to the furthest point and back so that each run contained four legs. There were eight nominal tracks: North, North east, East, South east, South, South west, West and North west. Flights were conducted on two successive days. The results for Day 1 are shown in Table 1.

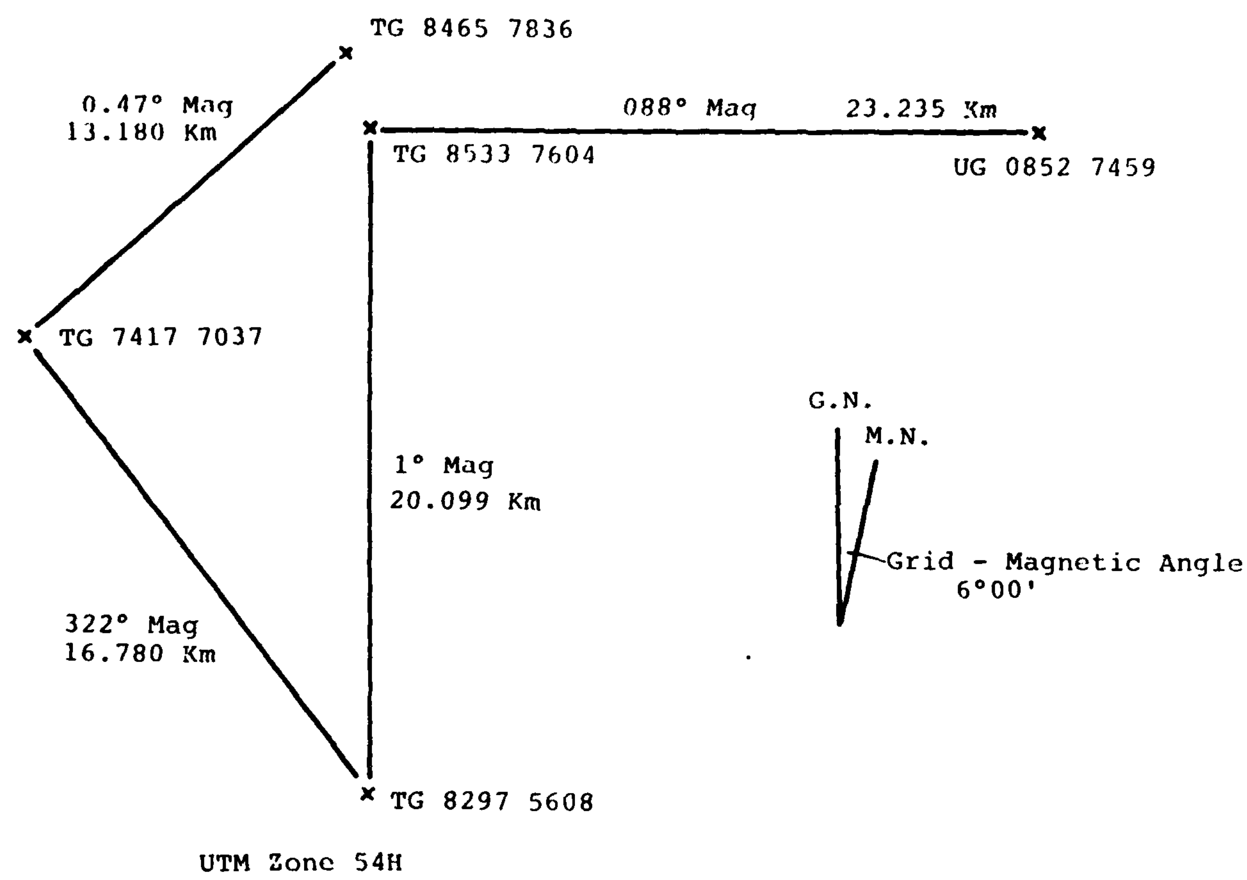

FIG. 1. TRACKS FLOWN FOR 'AIR CALIBRATION' EDINBURGH AREA.

TABLE 1 Air Calibration Results - Day 1

Track	est. heading (deg. mag.)	Deviation (cross-track error) (degrees)	along-track error (% of dist.)
N	001	-2.1	+0.3
W	268	-2.2	+0.3
N	001	-2.1	+0.1
W	268	-2.4	+0.3
E	088	-1.6	+0.3
W	268	-2.3	+0.3
S	181	-1.1	+0.8
NW	322	-1.9	+0.9
NW	322	-1.7	+0.6
NE	047	-0.5	+0.4
SW	227	-1.9	+0.8
SE	142	+0.2	+0.2
N	001	-1.3	+0.3
E	088	-1.9	+0.2
W	268	-2.1	+0.3
S	181	-0.3	+0.4

A curve was fitted by eye to the results obtained on the first day and was used to program a set of deviation corrections into the LDNS. A correction for +0.4% along-track (scale factor) error was also entered. The runs on the next day were used to check these corrections and accuracy was observed to be considerably improved. The results of these runs are shown in Table 2.

TABLE 2 - Air Calibration Results - Day 2

Track	est. heading (deg. mag.)	Deviation (cross-track error) (degrees)	along-track error (% of dist.)
N	350	-0.2	n/a
E	080	-0.2	-0.3
W	280	+0.2	-0.2
S	190	+0.4	-0.2
NW	322	+0.2	n/a
NE	030	+0.4	-0.5
SW	240	-0.5	-0.3
SE	142	-0.2	+0.1

The corrections were deemed to be generally satisfactory. The scale factor parameter in the LDNS was adjusted to +0.3 %. The cross-track error components are plotted in Figure 2. The LDNS corrections have been removed numerically for Day 2 runs to allow comparison with the earlier results. The fitted data used as LDNS deviation correction parameters are also shown. The bars on the plotted points show estimated standard deviation of observation error, based on an assumed s.d. of error in the leg end point positions of 20 metres (see below).

The TACTERM experiments proceeded and LDNS accuracy was deemed to be satisfactory for the next few days. Several days later an MC-2 compass calibrator was obtained and used to perform an electronic calibraton. The results are shown in Figure 2. These results are reasonable in isolation as they show the expected sinusoidal error pattern due to permanent magnetism ('hard iron') in the aircraft. The instrument technicians have high confidence in the accuracy of the MC-2 (reputed to be about 0.1 degrees). The only problem is that the electronic calibration disagrees wildly with the 'air calibration' results .

The MC-2 calibration results were used to program the LDNS deviation corrections and another flight was undertaken in the context of the TACTERM experiments. The consensus was that LDNS accuracy had decreased significantly as a result of the changed corrections. The errors are not available due to recording equipment failure. At this point the MC-2 calibration appeared to be invalid. The Air Calbration corrections were re-instated in the LDNS and its accuracy once again became satisfactory.

As part of the TACTERM experiments, a set of flights were performed in two areas, one in South Australia near R.A.A.F. Edinburgh, the other near Melbourne (Woodend). The tracks flown are shown on oblique views of the terrain in Figures 3 to 5. Each area corresponds to a 1:100000 map sheet (approx 44km N-S by 44/cos Latitude). The run numbers are merely codes, they are not sequential.

The set of relevant data recorded during these runs is shown in Table 3. Each run passed over a sequence of waypoints identified with a six (or less) letter name. The LDNS indicated position was recorded as each waypoint was overflown. The LDNS programmed corrections have not been removed. The relative positions of each waypoint and the last have been used to calculate the magnetic track and distance flown on each leg. Note that because of the wind there is a difference between magnetic track and heading but it does not make a difference to any conclusions drawn from these results.

The position error in the LDNS was obtained at each waypoint by subtracting the 'known' position at the waypoint from the LDNS indicated position. The change in position error over the leg was calculated by subtracting the position error at the start waypoint from that at the end.

The observed change in position error includes a contribution due to uncertainty (observation error) in the aircraft reference position at both start and end waypoints. These observation errors are assumed to be normally distributed with a zero mean and a standard deviation of 40 metres in both East and North components (or cross-

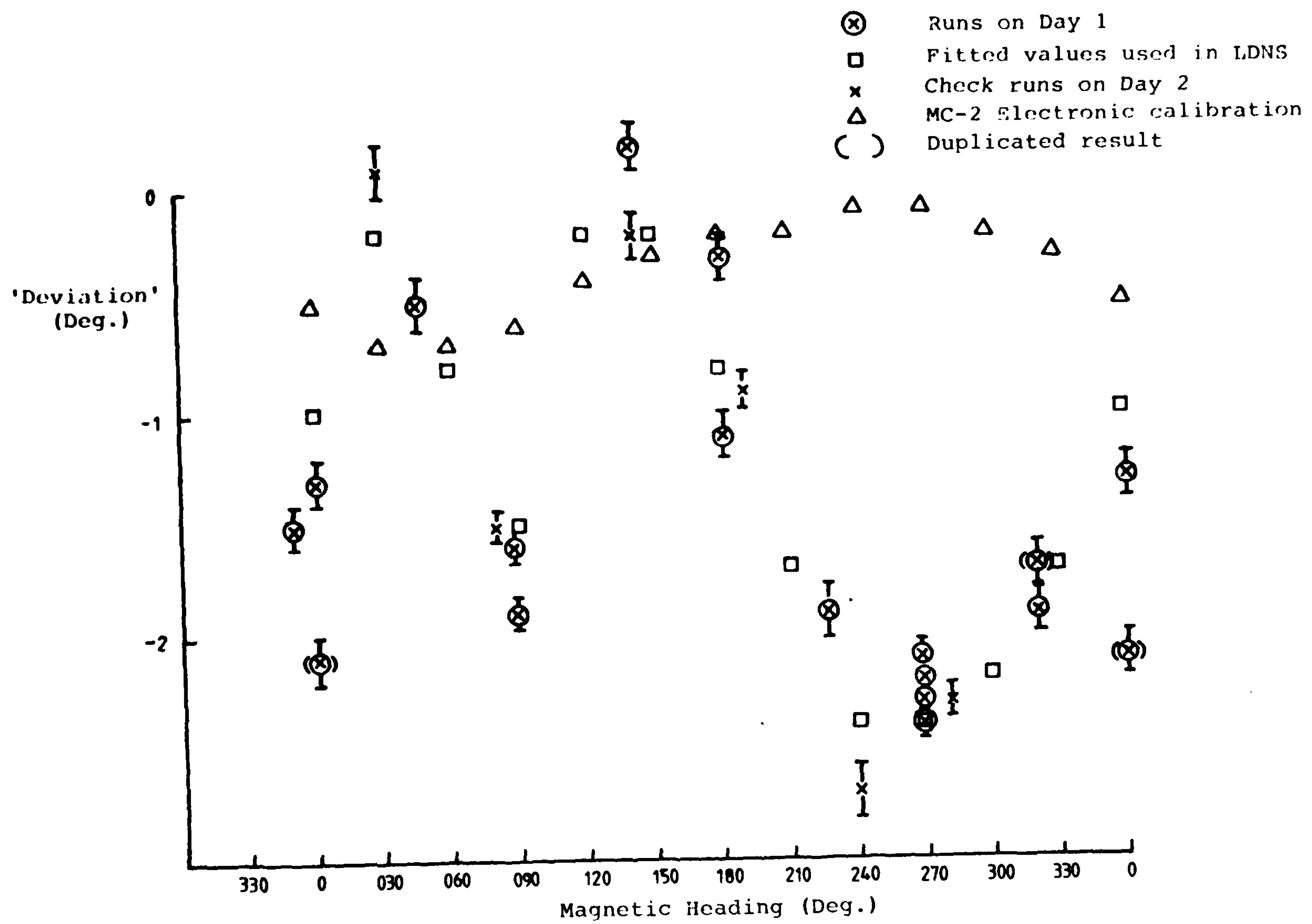

FIG. 2. 'AIR CALIBRATION' RESULTS

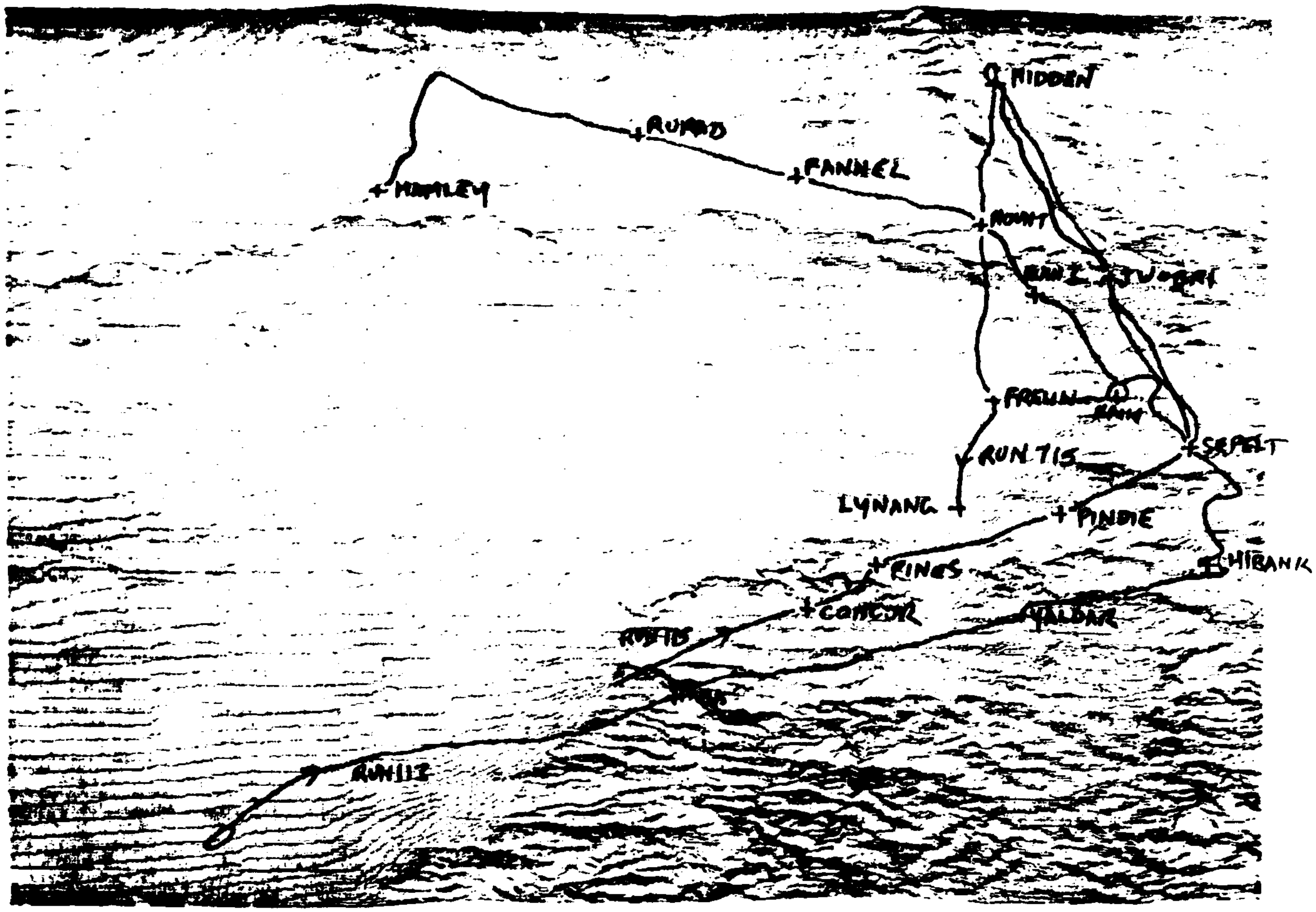

FIG. 3. EDINBURGH AREA

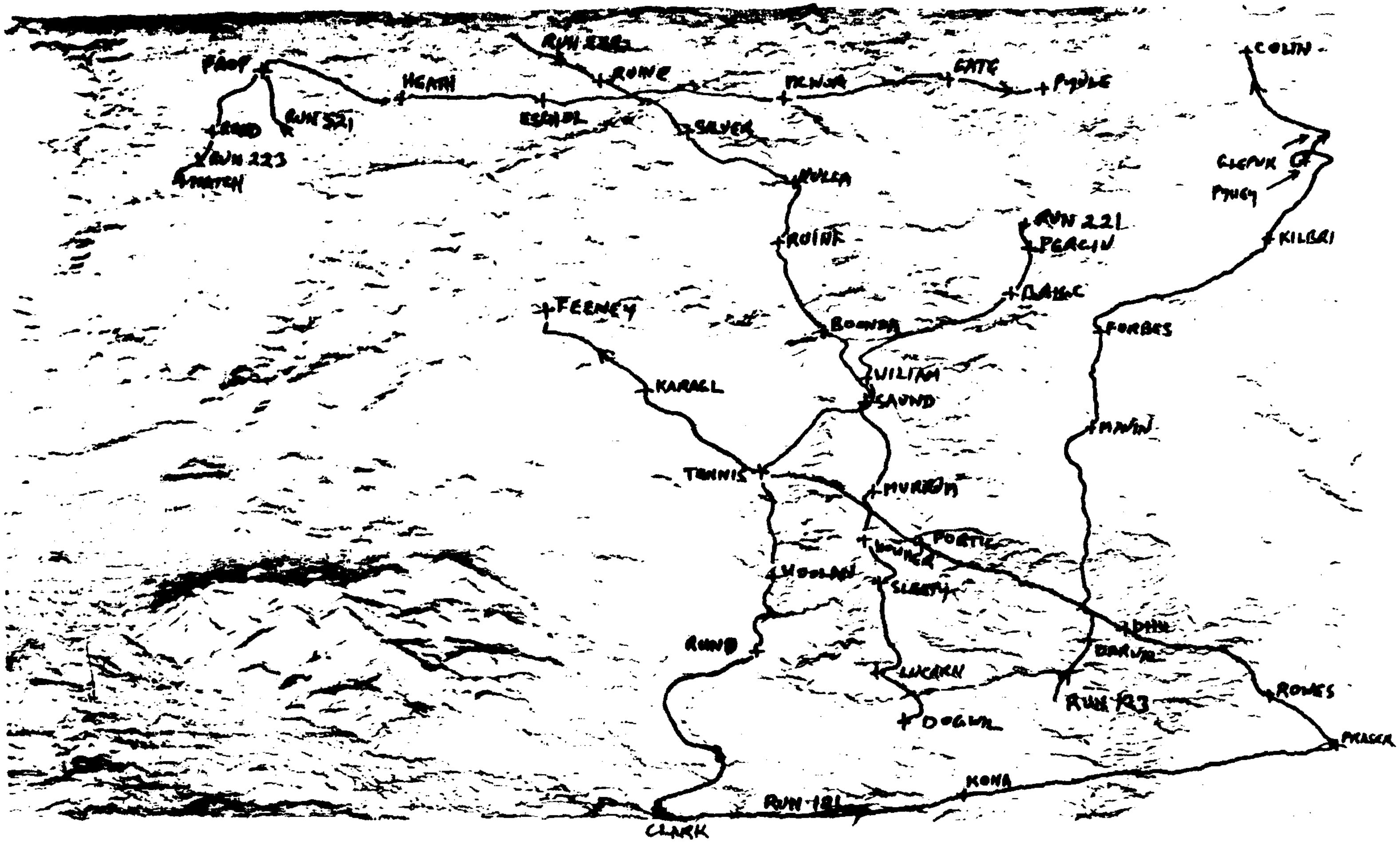

FIG. 4. *WOODEND AREA:* NOE TO 100 FT AGL

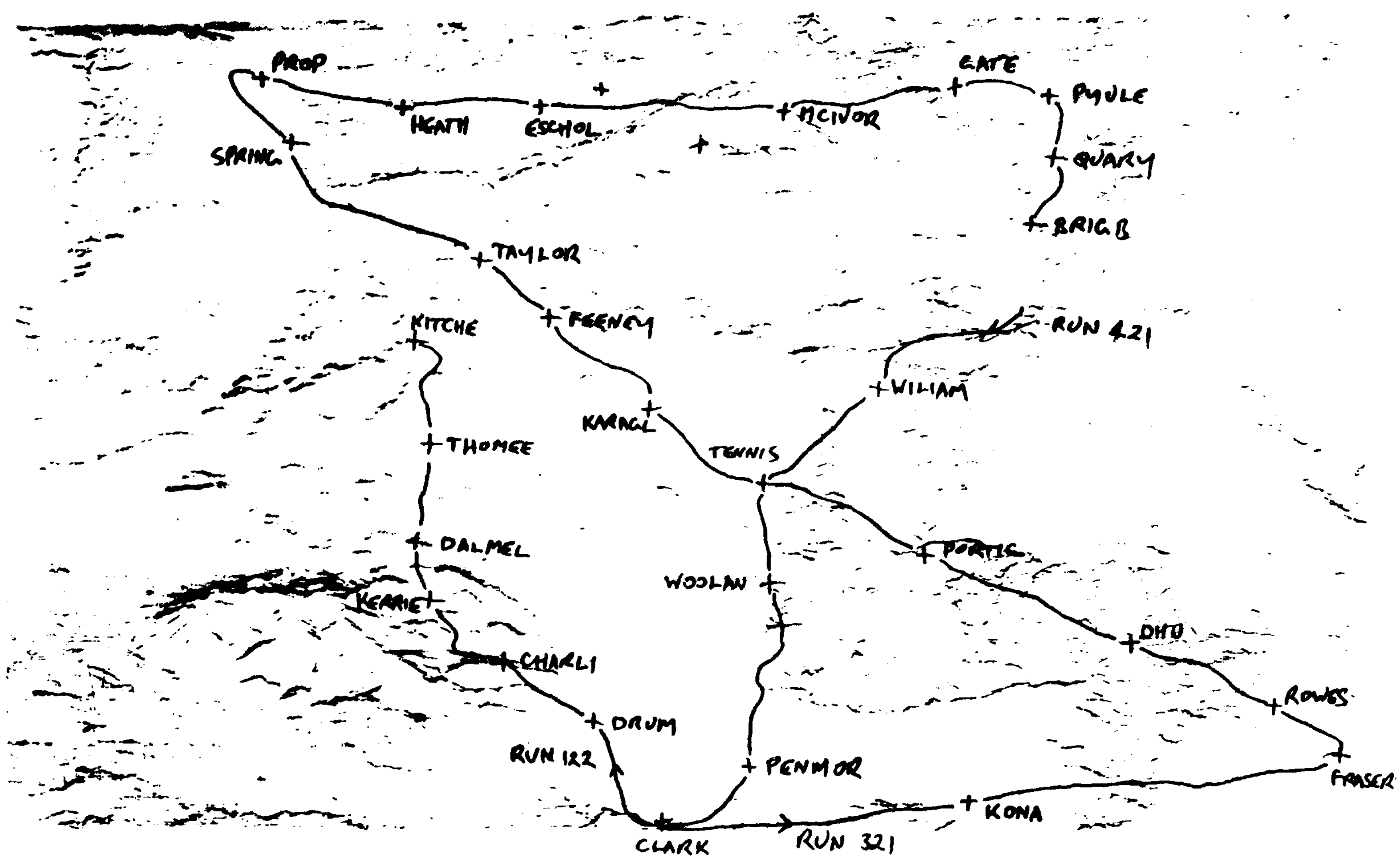

FIG. 5. WOODEND AREA 100 TO 300 FT AGL

TABLE 3

TABLE 3

DOPPLER ERROR ANALYSIS

RUN NO: 123

WAYPNT	TRACK(MAG.)	DIST.(M)	DEV.(DEG.)	EST.S.D.	ALONG (%)	EST S.D.
DARWAL	3	4429	1.0	0.7	-0.9	1.3
MAVIN	351	14260	-1.6	0.2	-0.1	0.4
FORBES	352	6692	-0.7	0.5	-0.2	0.9
KILBRI	30	8349	-2.1	0.4	-0.9	0.7
PYHEY	3	5390	-2.4	0.6	-1.5	1.1
GLEPUK	10	1740	-4.2	1.8	0.1	3.3
COLIN	327	6303	0.2	0.5	-0.8	0.9

RUN NO: 223

WAYPNT	TRACK(MAG.)	DIST.(M)	DEV.(DEG.)	EST.S.D.	ALONG (%)	EST S.D.
RUIND	190	4278	-1.3	0.7	-0.9	1.3
MATCH	186	3714	0.8	0.9	-1.5	1.5

RUN NO: 121

WAYPNT	TRACK(MAG.)	DIST.(M)	DEV.(DEG.)	EST.S.D.	ALONG (%)	EST S.D.
KONA	74	9665	1.2	0.3	-1.3	0.6
FRASER	69	12049	0.8	0.3	-0.4	0.5
ROWES	320	4337	-0.2	0.7	-0.6	1.3
DHU	305	6562	1.3	0.5	-0.4	0.9
FORTI[illegible]	302	8641	1.2	0.4	-0.7	0.7
TENNIS	305	7005	1.9	0.5	0.6	0.8
KARAGL	319	6661	0.9	0.5	-0.7	0.9
FEENEY	320	6387	1.2	0.5	-0.1	0.9

RUN NO: 521

WAYPNT	TRACK(MAG.)	DIST.(M)	DEV.(DEG.)	EST.S.D.	ALONG (%)	EST S.D.
PROF	337	4808	1.1	0.7	0.0	1.2
HEATH	104	4884	-0.7	0.7	-1.3	1.2
ESCHOL	86	4473	-0.1	0.7	-0.6	1.3
MCIVOR	80	7650	0.9	0.4	-0.4	0.7
GATE	70	5336	-0.0	0.6	0.2	1.1
PYULE	92	3011	0.4	1.1	-2.0	1.9

RUN NO: 221

WAYPNT	TRACK(MAG.)	DIST.(M)	DEV.(DEG.)	EST.S.D.	ALONG (%)	EST S.D.
PERCIV	164	2143	0.1	1.5	-1.1	2.7
BRIGC	181	3135	-0.7	1.0	0.4	1.8
WILIAM	206	7632	-1.1	0.4	-0.5	0.7
TENNIS	198	7155	-1.1	0.4	-1.0	0.8
WOOLAN	167	6827	-1.7	0.5	0.0	0.8
RUINB	176	5218	-1.1	0.6	2.3	1.1
CLARK	186	11020	-0.8	0.3	-0.9	0.5

RUN NO: 122

WAYPNT	TRACK(MAG.)	DIST.(M)	DEV.(DEG.)	EST.S.D.	ALONG (%)	EST S.D.
DRUM	334	6924	0.2	0.5	0.1	0.8
CHARLI	316	4200	-0.7	0.8	-0.9	1.4
KERRIE	318	5250	0.7	0.6	0.0	1.1
DALMEL	345	4043	-0.6	0.8	1.2	1.4
THOMEE	353	6915	-0.6	0.5	0.1	0.8
KITCHE	346	6655	-0.2	0.5	0.2	0.9

.../cont.

TABLE 3 (CONT.)

TABLE 3 (CONT)

RUN NO: 222

WAYPNT	TRACK(MAG.)	DIST.(M)	DEV.(DEG.)	EST.S.D.	ALONG (%)	EST S.D.
RUINE	129	4575	0.9	0.7	-1.0	1.2
SILVER	135	4703	0.5	0.7	0.4	1.2
NULLA	125	4833	1.9	0.7	0.2	1.2
RUINF	177	4298	-0.4	0.7	0.7	1.3
BOONDA	158	6443	0.3	0.5	-0.4	0.9
SAUND	156	5095	1.4	0.6	-0.7	1.1
MURRUM	167	6046	1.2	0.5	0.4	0.9
NOWHER	175	3349	0.6	1.0	-0.8	1.7
SLEEPY	163	3017	-0.5	1.1	0.6	1.9
LUCERN	171	5940	0.0	0.5	-0.3	1.0
DOGWIL	154	3403	-1.0	0.9	1.1	1.7

RUN NO: 321

WAYPNT	TRACK(MAG.)	DIST.(M)	DEV.(DEG.)	EST.S.D.	ALONG (%)	EST S.D.
KONA	74	9665	1.2	0.3	-0.7	0.6
FRASER	69	12048	0.3	0.3	-0.2	0.5
HOWES	320	4337	-1.1	0.7	-0.4	1.3
DHU	305	6562	0.1	0.5	-0.1	0.9
PORTIC	302	8641	0.7	0.4	-0.2	0.7
TENNIS	305	7006	1.7	0.5	0.6	0.8
KARAGL	319	6661	1.7	0.5	-0.6	0.9
FEENEY	320	6387	2.1	0.5	-0.3	0.9
TAYLOR	322	4319	4.2	0.7	1.3	1.3
SPRING	316	10561	0.7	0.3	-0.5	0.5
PROP	337	4809	0.1	0.7	2.1	1.2
HEATH	104	4884	0.7	0.7	1.6	1.2
ESCHOL	86	4475	0.8	0.7	-1.4	1.3
MCIVOR	80	7651	0.7	0.4	-0.0	0.7
GATE	70	5335	-1.0	0.6	1.6	1.1
PYULE	92	3012	1.1	1.1	-1.1	1.9
QUARY	168	4205	-1.9	0.8	-1.4	1.4
BRIGB	180	4598	-1.7	0.7	0.3	1.2

RUN NO: 421

WAYPNT	TRACK(MAG.)	DIST.(M)	DEV.(DEG.)	EST.S.D.	ALONG (%)	EST S.D.
WILIAM	206	7632	0.4	0.4	-1.4	0.7
TENNIS	198	7155	0.1	0.4	-0.5	0.8
WOOLAN	167	6827	1.0	0.5	0.7	0.8
PENHOR	175	12032	0.1	0.3	0.3	0.5
CLARK	204	4556	-2.6	0.7	-1.3	1.3

.../cont.

TABLE 3 (CONT.)

TABLE 3 (CONT)

RUN NO: 115

WAYPNT	TRACK(MAG.)	DIST.(M)	DEV.(DEG.)	EST.S.D.	ALONG (%)	EST S.D.
CONCOR	38	6916	-1.0	0.5	-0.3	0.8
PINES	25	3339	-0.3	1.0	-0.0	1.7
PINDIE	48	5804	-1.1	0.6	-0.1	1.0
SEPELT	31	5280	-1.4	0.6	-0.2	1.1
TWOERI	341	10580	-1.3	0.3	-0.2	0.5
HIDDEN	338	12099	-0.7	0.3	-0.1	0.5

RUN NO: 113

WAYPNT	TRACK(MAG.)	DIST.(M)	DEV.(DEG.)	EST.S.D.	ALONG (%)	EST S.D.
PARA	45	15271	-0.9	0.2	-0.8	0.4
YALDAR	51	10493	-1.8	0.3	-0.3	0.5
HIBANK	49	5842	-1.7	0.5	-0.9	1.0
NAIN	339	10466	-2.5	0.3	2.0	0.5
RUINS	333	6640	1.0	0.5	-0.2	0.9
MOUNT	334	4356	0.4	0.7	-1.6	1.3
FANNEL	293	5580	0.3	0.6	1.7	1.0
RURAL	292	4804	-0.2	0.7	-1.4	1.2
HANLEY	235	7645	0.2	0.4	-0.4	0.7

RUN NO: 715

WAYPNT	TRACK(MAG.)	DIST.(M)	DEV.(DEG.)	EST.S.D.	ALONG (%)	EST S.D.
TWOERI	341	10584	-0.7	0.3	-0.5	0.5
HAWKER	338	6232	-0.7	0.5	-0.1	0.9
HIDDEN	336	5873	-0.8	0.5	0.8	1.0
MOUNT	174	8601	-1.3	0.4	-0.1	0.7
FRELIN	171	11030	-0.6	0.3	-0.2	0.5
LYNANG	180	6411	-1.1	0.5	-0.1	0.9

track and along-track). This figure is higher for these runs than for those of the Air Calibration because of the high dynamic environment (often manoeuvering at full speed) which caused additional uncertainty in positioning the aircraft over the waypoints.

The estimated variance of the observation error component in the change in position error is obtained by summing the estimated variances of observation error at both ends of the leg. The standard deviation is the square root of that value, and can be expressed as an angle (for cross-track error) or a proportion (along-track) by dividing the s.d. by the distance between the waypoints. These are expressed in degrees and percent of distance flown respectively in the results shown in Table 3.

The cross-track errors in Table 3 are summarised in Table 4 as follows. The tracks flown have been divided into twelve sectors: 0 to 30 degrees, 30 to 60 & etc.. A weighted mean cross-track angular error and estimated standard deviation of observation has been calculated for the tracks in each sector. These have been calculated as follows.

$$\text{Mean cross-track error } \bar{f}(k) = \frac{\sum_{i=1}^{n} f_i(k)\, w_i(k)}{n(k)\sum_{i=1}^{n} w_i(k)}$$

where $w_i(k) = 1/s_i(k)$ ($s_i(k)$ is the estimated s.d. of error *in observation of* $f_i(k)$), k is the track sector and $n(k)$ is the number of observed tracks in the sector.

$$\text{Standard deviation } S(k) = \sqrt{\frac{\sum_{i=1}^{n} s_i^2(k)\, w_i^2(k)}{n(k)\sum_{i=1}^{n} w_i^2(k)}} = \sqrt{\frac{1}{\sum_{i=1}^{n} w_i^2(k)}}$$

The along-track errors, similarly weighted, are also shown in Table 4.

TABLE 4 Summary of LDNS Errors

Weighted Cross-track Error ('Deviation')

(All values in degrees)

hdg.	000–030	030–060	060–090	090–120	120–150	150–180	180–210	210–240	240–270	270–300	300–330	330–360
mean	−0.3	−0.2	+0.1	+0.1	+0.4	+0.0	+0.0	n/a	n/a	+0.1	+0.1	−0.0
S	0.4	0.1	0.1	0.4	0.4	0.1	0.2			0.4	0.1	0.1
n	4	7	10	4	3	16	11	1	0	2	17	16

Weighted Along-Track Error (Scale Factor)

Mean: 0.00% S: 0.08% n:91

These figures give no apparent cause for alarm. The mean errors are small compared to the observation error and are a considerable improvement on the uncompensated compass errors observed in the 'Air Calibration'. It appears that the corrections derived from the 'Air calibration' were effective.

The accuracy of the LDNS expressed as CEP (50%) recorded during these runs is shown in Figure 6 as a function of distance travelled. This summary has been obtained by selecting intervals of total distance travelled (from the start of each run) in which at least one waypoint for each run occurred (provided the run went as far as that interval). Where more than one waypoint in a particular run occurs within the interval only the last (max. distance) waypoint is used in the calculation. The CEP of the LDNS errors at the waypoints in each interval is plotted against the mean distance along track of the waypoints used for the calculation in the interval. The bars parallel to the "distance travelled" axis show +/- 1 s.d. of the dispersion in distance of the waypoints used. The vertical bars show 95% confidence intervals of the CEP (based on the size of the sample in the interval). These results are close to the CEP of 1% of distance travelled generally accepted to be representative of doppler navigation systems.

3. DISCUSSION

The main error in the LDNS observed during these trials was in the cross-track component. It is unlikely that the LDNS itself is the source of this error. This can be established by thinking through the processes involved in determining the LDNS indicated position. The velocity of the aircraft is determined by measuring the doppler shift along four sequentially generated beams (switched at approx 7.5 Hz.) each one of which has a fixed attitude relative to the aircraft fuselage. The velocity vector of the aircraft relative to the surface of the Earth is obtained in aircraft body axes by a fixed linear transformation of the doppler shifts. This vector is then transformed into 'local level' co-ordinates by rotation transformations in roll and pitch using angles obtained from the aircraft vertical gyro. The horizontal components are expressed along, and across, the aircraft heading. They are linear combinations of doppler shift in the four beams and their errors are functions of doppler processing error, roll angle error and pitch angle error. All these errors are independent of heading yet the errors observed in the LDNS are strongly heading dependent.

The last stage in the sequence of transformations of velocity is a rotation through the true heading, obtained by adding programmed local magnetic variation to compass (magnetic) heading. The resultant velocity vector, in geographic co-ordinates, is integrated from the programmed initial position to obtain current indicated position. It can readily be seen that this last transformation does not change the magnitude (speed) of the velocity vector so heading error has no first

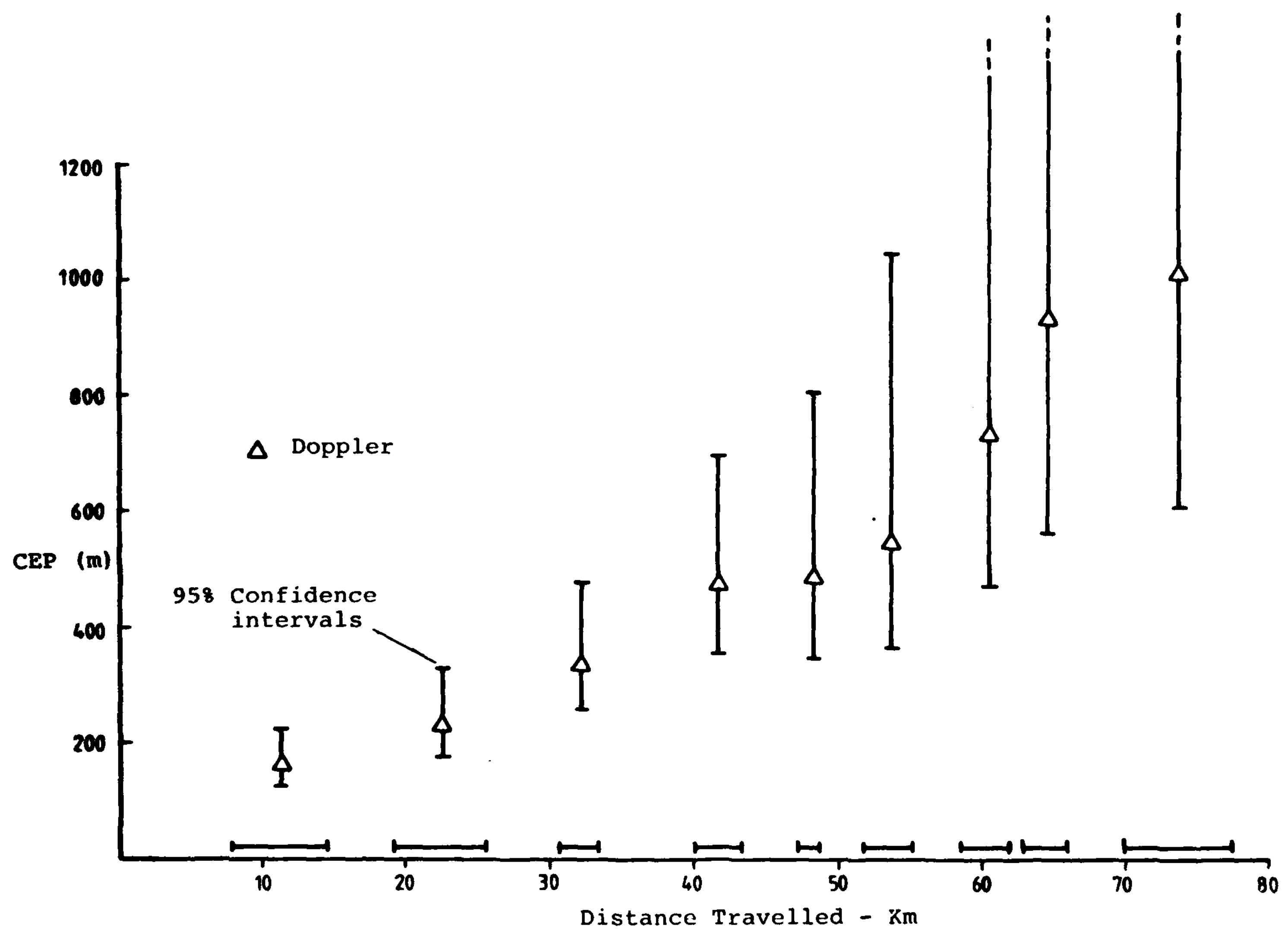

FIG. 6. TACTERM - HELICOPTER TRIALS

order effect on along-track error. It does, however, have a marked effect on the cross-track component of error by 'deflecting' the velocity vector. The resultant cross-track velocity error is the aircraft speed times the heading error (in radians) to first order. As the observed LDNS errors are large and heading dependent in the cross-track component and small in the along-track component the evidence points strongly to heading error as the major error source (a well-known result).

There remains the mystery, however, of the difference between the Air Calibration and both the MC-2 and Wild Datum ground swing results. It is possible, given the data available, to suggest a cause. Magnetic compass deviation, in straight and level flight at any given place and time can be expressed (to first order) as the sum of a heading-independent bias "A" and a heading-dependent sinusiodal term which will be called "G" for convenience. This may be expressed as

$$f(\text{heading}) = A + G \sin(\text{heading} + \text{phase})$$

where f is the compass deviation.

The phase is related to the orientation of the aircraft's permanent magnetic field with respect to its longitudinal axis and can be regarded as being constant over the two days of the calibration flights. G is a function of the relative strength of the aircraft's magnetic field compared to that of the Earth. A is the sum of misalignment of the magnetic sensor in the aircraft and error in knowledge of the direction of the horizontal component of the Earth's field with respect to true north (error in magnetic variation). Both A and G vary from place to place. The rate at which they vary as a function of distance travelled depends on the local magnetic properties of the Earth.

The sum of the error component due to permanent magnetism on reciprocal headings at the same place and time will be zero, i.e.

$$f(h)+f(h+180^\circ)=2A \qquad \text{——(1)}$$

Similarly

$$f(h)-f(h+180^\circ)=2G \sin(h+\text{phase}) \qquad \text{——(2)}$$

for any heading h.

The A and G sin(h+phase) components have been calculated in this way for those legs of the Air Calibration for which such 'pairs' of reciprocal headings were recorded in the same flight.

If the magnetic environment had been constant for all flights the values of A determined by Equation 1 would have been constant and the values of G sin(heading+phase) would have been a pure sinusoid with respect to heading. A difference in magnetic variation alone between air calibration legs would result in a change in the observed value of A, while a difference in the Earth's magnetic field strength would be reflected in a change in G. Such differences were observed in

the air calibration results shown in Figures 7 & 8.

It can be seen from Figure 1 that the East-West headings were flown over the leg furthest displaced from the others. The eastern half of this leg lies over rolling hills and gullies while the other legs lie over flat coastal plains. The E-W leg is thus the one most likely to be magnetically different from the others. The results shown in Figures 7 & 8 support this expectation.

The components calculated from the legs flown the next day are shown for comparison even though, because of a strong wind, the 'reciprocal' headings are not really reciprocal. The magnetic track has been used to plot the values. The skeleton of a sinusiod can be seen in the G values if the E-W headings are excluded. Note that the data in these graphs the data are duplicated on reciprocal headings(see Equations 1 and 2).

Figures 7 & 8 hint at the place-to-place and day-to-day changes in magnetic environment that can contribute to compass error and an examination of Table 2 will give further illustration of this.

4. CONCLUSIONS

The accuracy of the LDNS in combination with the AN/ASN-43 compass observed during the trials was approximately 1% of distance travelled. Although this is satisfactory it should be noted that because the experiment was designed for other purposes, the distribution of headings flown was not uniform and contained a relatively small number of examples in the sectors that might be expected to give trouble.

The position errors observed are almost certainly due to the magnetic compass system, not the LDNS itself.

The observed place-to-place and day-to-day changes in compass error due to magnetic influences were sufficiently large as to make pointless any attempt to improve LDNS accuracy by improved compass calibration procedures.

The accuracy of the total system would be improved considerably if the AN/ASN-43 were replaced by a modern Attitude and Heading Reference System (AHRS) which could be integrated with the LDNS and thus reduce or eliminate the sensitivity of position error to magnetic influences.

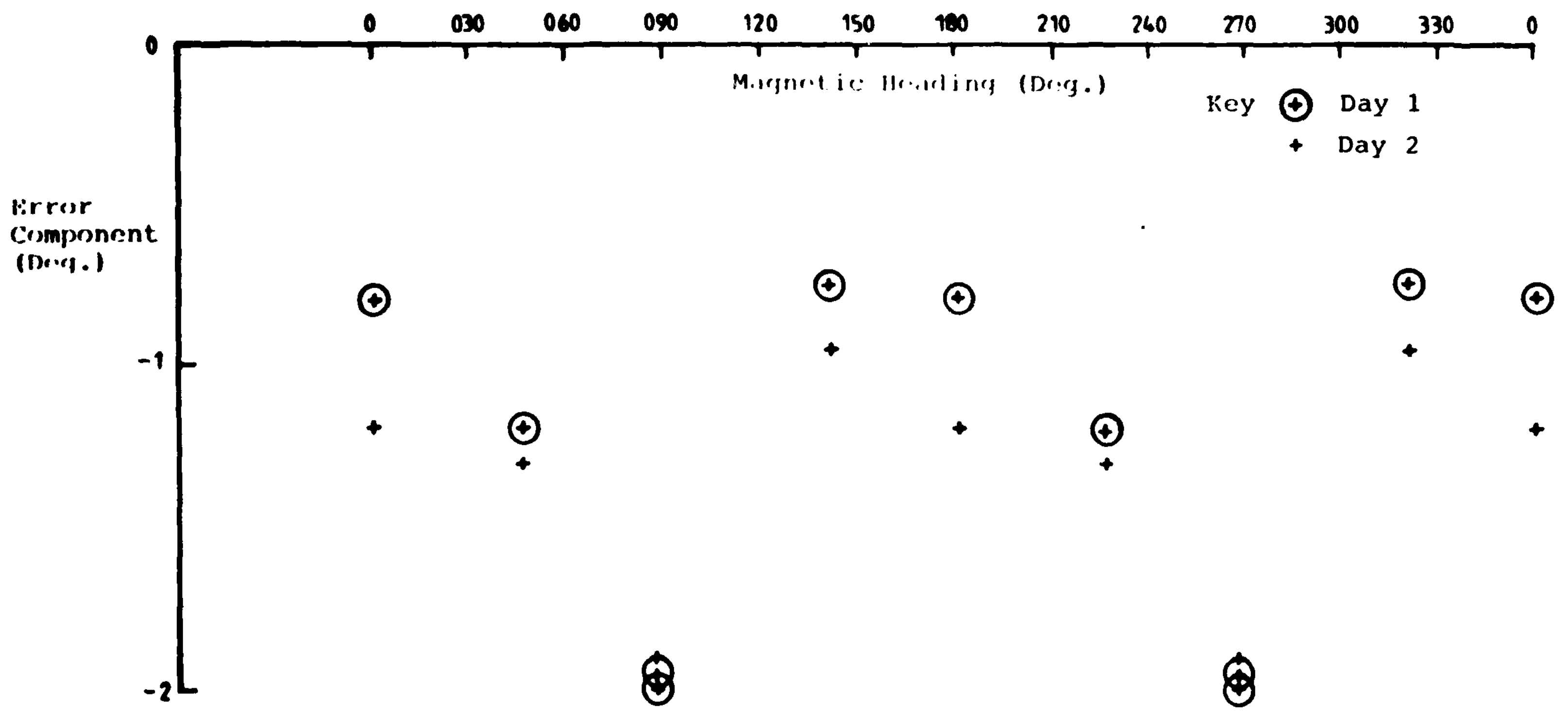

FIG. 7. AIR CALIBRATION - 'A' COMPONENT

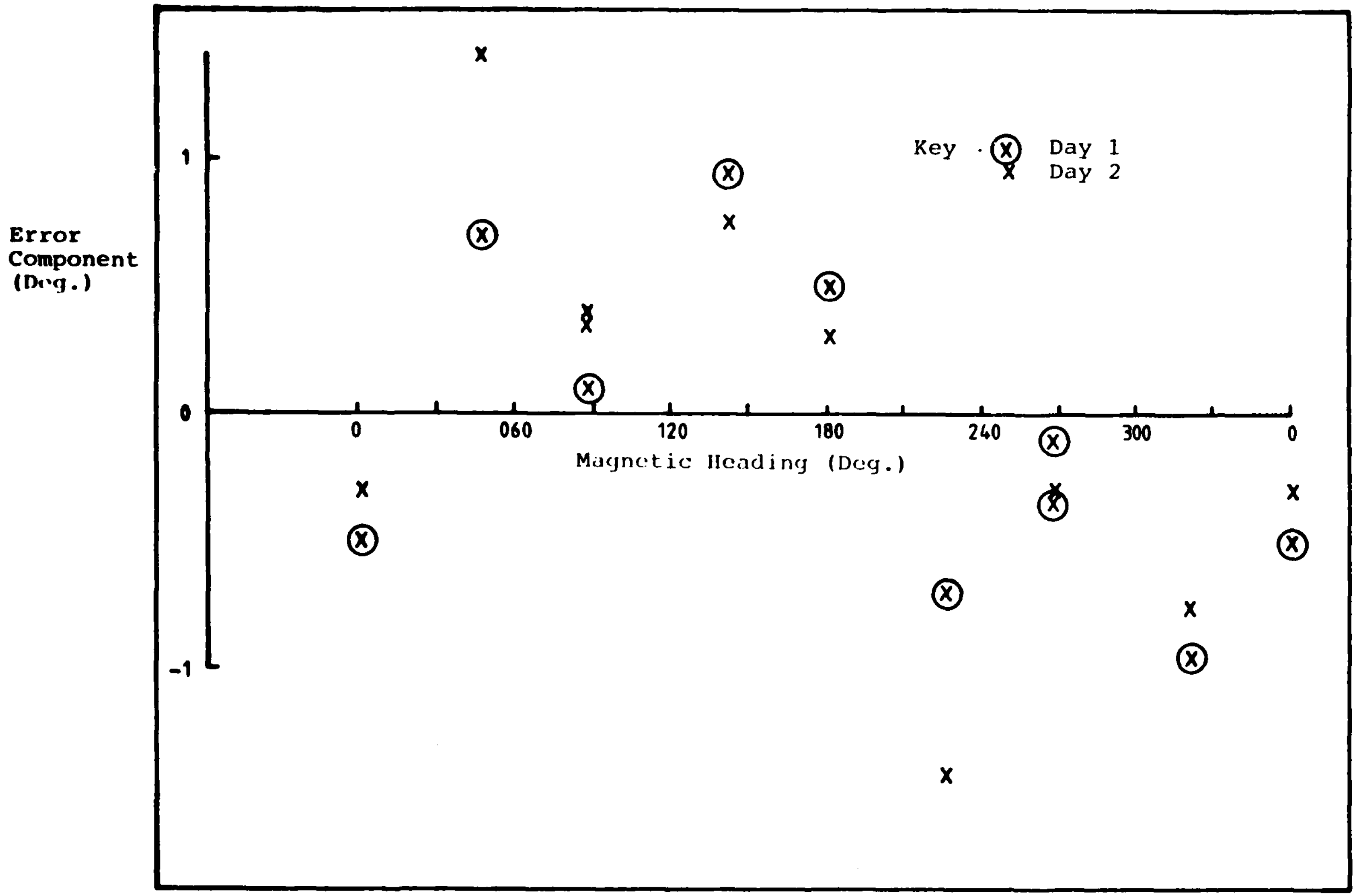

FIG. 8. AIR CALIBRATION - 'G SIN (HEADING & PHASE)

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APPENDIX 1

Navigation Terms and Basics of Magnetic Compasses

An illustration of the navigation terms used in this paper is shown in Figure 1.1. The aircraft's magnetic heading is determined by a compass, which is normally a directional gyroscope slaved to a pendulous magnetic sensor ("fluxgate") situated in as magnetically 'clean' a part of the aircraft as possible. In the UH-1H this sensor is in the tail boom. In straight and level flight the sensor measures the relative direction of the local horizontal component of the Earth's magnetic field. In the AN/ASN-43 any difference between the heading indicated by the gyro and the magnetic heading indicated by the fluxgate causes the gyro to be slewed at a maximum rate of approximately 2 degrees per minute. The gyro is thus used as a means of stabilizing the magnetic information which would otherwise be disturbed by aircraft manoeuvres, turbulence and small scale magnetic anomalies(close to the ground). For our purpose of analysis of navigation performance the compass can be regarded as a purely magnetic one because the time it takes to adjust to changes in magnetic heading as perceived by the fluxgate is generally small compared to the times taken in navigating between waypoints.

Errors (deviation) in a magnetic compass have three main sources. The first, known as the "A" component is a simple bias and is independent of heading. It is a combination of the misalignment of the fluxgate with the aircraft centreline, internal fluxgate bias and error in the assumed local magnetic variation. The second source of error is permanent magnetism in the aircraft structure(also known as "hard iron"). The magnetic field due to this "hard iron" is fixed with respect to the aircraft (over the time intervals considered here) and so has an effect on the field around the fluxgate that depends on the aircraft's orientation in the Earth's field, i.e. its heading. The effect is an error that varies as sin(heading+phase). This "hard iron" component of error is usually expressed as B sin(heading) + C cos(heading). For the purposes of our discussion in this paper it is more convenient to express this term in the (equivalent) form G sin(heading+phase).

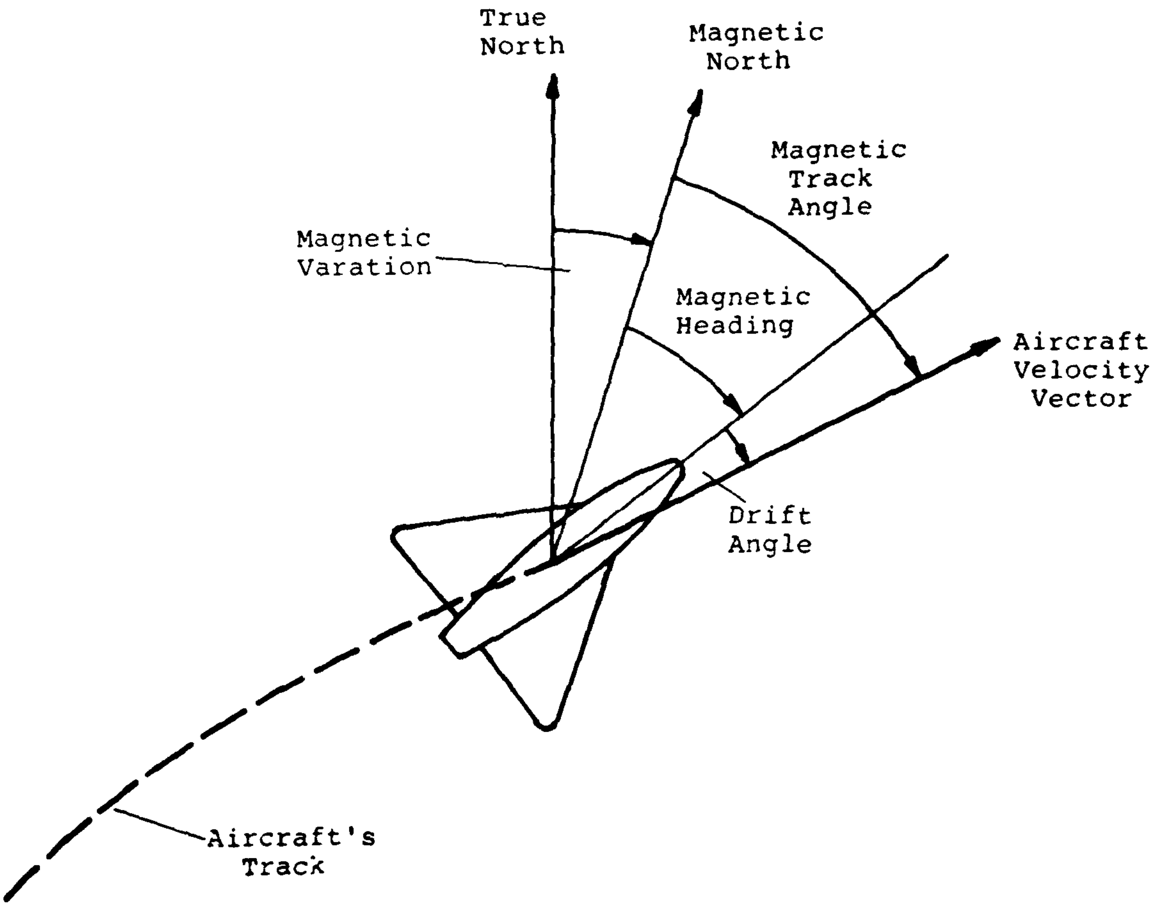

FIG. 1.1 NAVIGATION TERMS

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Navigation Doppler navigation Magnetic compasses Gyro compasses	17070

16. Abstract

Data on the accuracy of the Lightweight Doppler Navigation System (LDNS) fitted to a Royal Australia Air Force UH-1H helicopter were gathered as a by-product of an experiment on the TACTERM navigation system. The observed accuracy was found to be close to 1% of distance travelled, a figure generally considered to be representative of modern doppler navigation systems.

The dominant source of LDNS position error was magnetic compass error which in turn appeared to be dominated by spatial and temporal variations in the local magnetic field.

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16. Abstract *(Contd)*		
17. Imprint Aeronautical Research Laboratories, Melbourne.		
18. Document Series and Number Systems Technical Memorandum 70	19. Cost Code 72 3380	20. Type of Report and Period Covered
21. Computer Programs Used		
22. Establishment File Ref(s)		

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